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ORIGINAL ARTICLE

Predictability of nominal dental implant resonances

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ABSTRACT
A piezo based sensor system used for dental implant stability measurement has been modelled to predict the nominal resonance frequency of the implant and the total system. The modeling has been done considering the thickness and radial mode of vibration as these are the two dominant mode of vibration for a radial disk piezo element. As piezo buzzer has been used in this study to develop the sensor, these two modes of vibration has been considered and then compared to infer the suitable mode of vibration for this particular application where the frequency range varies between 1 to 20 KHz. The sensor attached with dental implants have been analysed depending upon this and an expression has been proposed to predict the nominal resonance frequencies of four types of dental implant systems. These predicted nominal resonance frequencies of the dental implants will help to predict the behaviour of the total system when placed inside the jaw to measure the actual in vivo dental implant stability. This present study will provide a guideline not only towards the choice of proper dental implant and proper mode of vibration but also towards the choice of proper excitation voltage while measuring the stability of the dental implant using Resonance Frequency Analysis (RFA)technique.
Keywords: *Resonance frequency analysis, dental implant stability, modelling, radial mode of vibration, thickness mode of vibration, impedance response, dental implant*

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INTRODUCTION

Modelling of a RF based sensor system attached with dental implant has been done to predict the nominal resonance frequency value for the dental implant. The dental implant, when placed inside the jaw, is to be monitored to ensure its bonding with the jaw and hence its stability. Stability measurement of the dental implant can be done using Resonance Frequency Analysis (RFA) technique. RFA technique requires a sensor system which consists of a circular piezo element, supported by a cross shaped aluminium substrate. The aluminium substrate has two arms, one attached with the piezo and the other is rectangular in shape, perpendicular with the first arm having a groove at the end to hold the implant. Several researchers [1], [2], [3], [4], [5] have studied the sensor characteristics in-vitro for this purpose. The sensor used by Meredith [1] consists of an L-shaped metallic strip attached to a square shaped thin piezo sensor-actuator while Sunil et al. [5] used a cross type metallic strip attached to a thin radial disc piezo sensor-actuator. This sensor system is attached with dental implant for stability measurement purpose. The main purpose of the modelling is to predict the nominal resonance frequency of the total system, (i.e. sensor, implant and the jaw). The total system should have a suitable resonance frequency so that it does not affect the implant and the jaw. The dental implant will show its changing resonance with the change in bonding between the jaw and the implant. This changing resonance frequency will be around the nominal resonance frequency which has already been predicted from the modelling. Thus it will be easier to capture the change in resonance frequency of the implant-bone interface; hence the stability of dental implant, as the starting frequency is already known. Piezo element can vibrate in different modes depending upon their geometry, polling directions and the frequency of the exciting signal. In [6], some common geometries are mentioned which can be used to characterize piezoelectric materials along with the polling direction. Among different modes of vibration, thickness and radial mode of vibrations are applicable for radial disc piezoelectric materials. Among these two modes of vibrations, thickness mode is applicable for high frequency range and radial mode is for low frequency range. But the actual high and low frequency range is not known, it varies for different piezo elements. In this study, the operating frequency range is audio frequency range, i.e. 1 to 20 KHz. In this operating frequency range, the actual mode of vibration cannot be predicted theoretically because there is no such guideline which tells the appropriate mode of vibration for radial disc piezo elements. That is why, the sensor system has been modelled in both of the modes and both of them are validated to ensure the appropriate mode of vibration. The sensor when attached with dental implant shows different characteristic than the only sensor system. The model of the total system has been done to predict this difference, which is mainly in the resonance frequency. In the model of the total system, the characteristics of the implant affecting the resonance frequency has been incorporated, so that, for a predefined nominal resonance frequency, the proper dental implant can be chosen.

MATERIAL AND METHODS

The sensor system:

A lossless radial disc piezo element is taken for the sensor system. The electrodes are attached on both sides. Two wires are soldered on the electrodes to give the excitation voltage. Its diameter is much larger than its thickness. The piezo material used in this work is Lead Zirconate Titanate (PbZrx Ti1-xO3) with the weight percentage of Pb, Zr-Ti and O3 as ~50%, ~20% and ~20% respectively. The rest ~20% is impurities like Cu, Zn, Zr etc. The materials of the electrodes are silver (Ag) and Cu-Zn alloy. The sensor consists of such a radial disc piezo element glued with a aluminium strip with two arms, one is cross shaped and attached with the piezo, other arm is extended one with rectangular shape and perpendicular with the other arm and having a groove at the free end to hold the implant. This sensor system has been named as cross type sensor. The actual sensor analysed are shown in the Figure1.

Figure 1: Piezo based Cross Type sensor for Dental implant stability Measurement

Modelling in thickness mode:

The sensors are modelled considering the thickness mode of vibration, using the impedance equation [7]

$$Z_{st} = \frac{i}{\omega a_p} [-Z_1 + Z_2 + Z_2 - Z_3 + Z_4] \quad \text{.......(1)}$$

Where,

$$Z_1 = \beta^S_{33} + h_{33} \quad \text{.......(2)}$$

$$Z_2 = \frac{U_L}{U_R} \sin(\frac{\omega}{2f_P}) \quad \text{.......(3)}$$

$$Z_3 = U_S \frac{U_L}{U_R} \frac{C^D_{ss}}{v_P} (\cos(\frac{\omega}{2f_P}) - 1) \quad \text{.......(4)}$$

$$Z_4 = h^2_{33} U_S (\cos(\frac{\omega}{2f_P}) - 1) \quad \text{.......(5)}$$

$$U_S = \frac{v_S}{C^D_S \omega \tan(\frac{\omega d}{v_P})} \quad \text{.......(6)}$$

$$= [\frac{h_{ss} v_P}{C^D_{ss} \omega} + U_S h_{33} \sin(\frac{\omega}{2f_P})] \quad \text{.......(7)}$$

$$U_R = \cos(\frac{\omega d}{v_P}) + U_S \frac{C^D_{ss} \omega}{v_P} \sin(\frac{\omega d}{v_P}) \quad \text{.......(8)}$$

Modelling in radial mode:
Similar to the thickness mode, the sensor systems have been modelled in radial mode of vibration in terms of its impedance. The impedance equation of the system in radial mode is given as [8]

$$Z_{SR} = \frac{Z_1 \frac{Z_1 + Z_S}{N^2}}{Z_1 + \frac{Z_1 + Z_S}{N^2}} \quad \text{.......................................(9)}$$

$$Z_S = \frac{2\pi l\, C_{11}^S}{\omega} \left(1 - \sigma^S - J\left(\frac{\omega r p}{v_S}\right)\right) \quad \text{.......................................(10)}$$

$$Z_1 = \frac{1}{i\omega C_p} \quad \text{.......................................(11)}$$

$$Z_2 = \frac{2i\pi d\, C_{11}^P}{\omega} \left(1 - \sigma^P - J\left(\frac{\omega r p}{v_P}\right)\right) \quad \text{.......................................(12)}$$

$$N^2 = 4\pi^2 a_p^2\, k_p^2\, \epsilon_{33}^S\, C_{11}^P \quad \text{.......................................(13)}$$

$$C_p = \frac{\pi\, a_p^2\, \epsilon_{33}^S}{d} \quad \text{.......................................(14)}$$

Experimental Procedure:
Twelve similar cross type sensor systems are taken for experiment. They are excited with a sinusoidal voltage of 1 volt p-p and variable frequency of 1-20 KHz. The responses of the sensor systems are taken with a 4294A Agilent LCR meter in terms of their impedance in ohm vs. frequency in KHz. Three similar responses are taken for each of the sensor systems and an average of the three responses is calculated and the average responses have been taken to validate the model.

RESULTS AND DISCUSSION
The average responses of the sensor systems are simulated using the above mentioned impedance equation in thickness and radial mode of vibration in MATLAB 7.0. A particular sensor system response has been taken as nominal response and simulation has been done to replicate the experimental response of the nominal set. Then the same model has been used to replicate the other sensor responses. Variations in the parameter values in the model, to match it with the experimental responses of other sensors, are noted. The resonance frequencies of the piezo elements and sensors are kept same with the assumption that the total sensing system vibrates as a single entity. The parameter values taken to validate the model with respect to the experimental results are given in the Table 1 & Table 2 in thickness mode and Table 3 & Table 4 in radial mode.
The parameters used in thickness mode, D_3, C_{33}^D, C_S^D, β_{33}^S, v_P, and v_S are having same values for all the sensors. Similarly the parameters used in radial mode, C_{11}^P, C_{11}^S, $\varepsilon^P{}_{33}$, v_P, and v_S are having same values for all the sensors. Only the real component of coupling coefficients and resonance frequencies of the sensors are different for different sensors in both of the modes. In both modes, the resonance frequencies are taken from the experimental responses and the coupling coefficients have been chosen to match the corresponding sensor responses.
In [7], Sherrit et al estimated different material constants of a supported radial disc piezo element vibrating in thickness mode of vibration. The parameter values estimated in this paper are comparable with the values estimated by Sheritt et al. The differences are mainly in the imaginary component values. This is mainly due to the fact that our sensor differs from the system used by Sherrit et al in size of the piezo element, the shape & size of the metal sheet attached with the piezo, the material of the metal sheet and also in the range of frequency used.
As given in [7] the real components of β_{33}^S, h_{33}, C_{33}^D, C_S^D are expected to be in the order of 10^7 to 10^{15}, 10^6 to 10^{11}, 10^9 to 10^{11} and 10^9 to 10^{11} respectively in thickness mode, whereas in our case the values are in the order of 10^{12} , 10^{10}, 10^{10} and 10^{11} respectively, which are comparable. In radial mode analysis the real component values of the parameters C_{11}^P, C_{11}^S and $\varepsilon^P{}_{33}$ are estimated in the order of 10^6, 10^{11} and 10^{-4} respectively. The imaginary components of each parameter indicate mainly the loss of energy between the piezo and the metal sheet. The high values of imaginary components of the above mentioned system parameters for the sensor systems as compared with [7] indicate more loss of energy between the piezo and the metal sheet than the systems used by Sherrit. This may be due to different shape and size of piezo as well as the sensor, the amount of adhesive used the capacitive effect of the sensor systems as well as the connecting wires etc.

Choice of appropriate mode of vibration of the cross type sensor:
To choose appropriate mode of vibration, two sets of simulated responses are taken for each sensor. One set has been taken by changing only the resonance frequencies for different sensors but the other

parameter values are kept same for all. Other set has been taken by changing the resonance frequencies and the coupling coefficients values for different sensors keeping the other parameter value same for all. Error curves have been plotted for both of the sets in two modes. The Fig. 2 and Fig. 3 are showing the experimental response, simulation responses and the respective error curves for a typical set in the frequency range of 5000-11000 KHz in both of the modes.

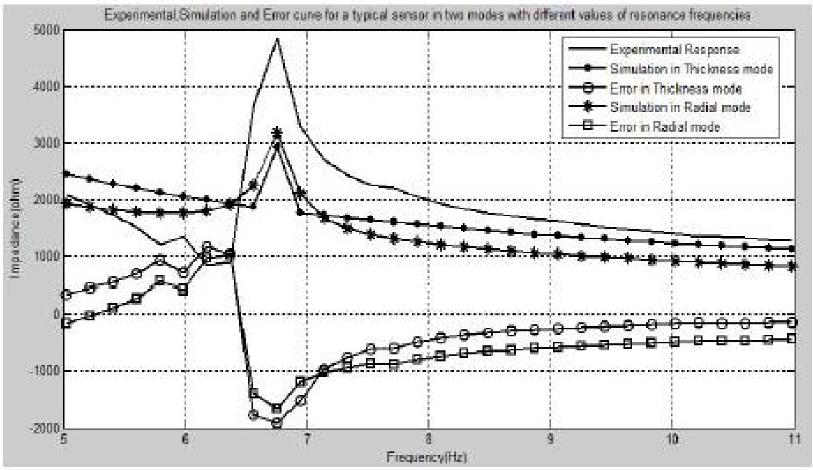

Fig. 2 Experimental and Simulation curve of a typical sensor with different resonance frequencies

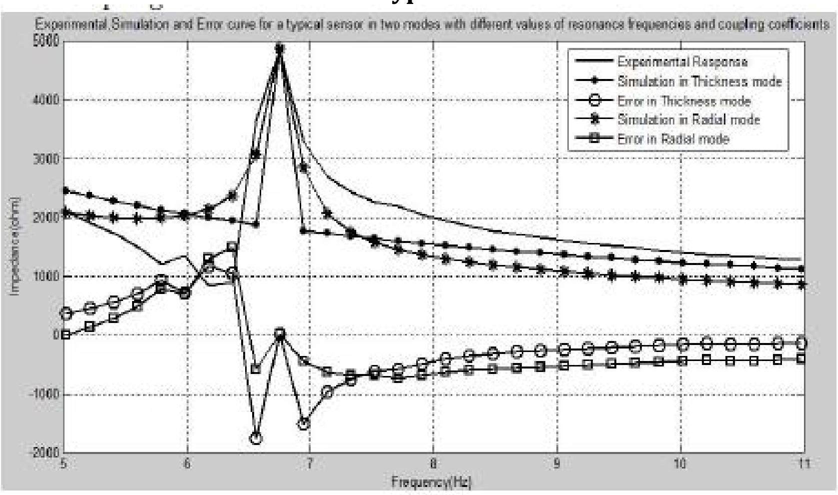

Fig. 3 Experimental and Simulation curve of a typical sensor with different resonance frequencies and coupling coefficients

To compare the modelling in two modes of vibrations a statistical analysis has been done. To analyze, two typical parameters have been decided, named as:

1. [MSE (with changing coupling coefficient) / Mean area under the experimental curve] X100%
2. [MSE of individual set (w/o changing coupling coefficient) / MSE of nominal set(w/o changing coupling coefficient)]X100%

Where MSE indicates Mean Square Error for both of the modes and depending upon the these two parameters a comparison has been done.

As mentioned earlier, two sets of simulated responses are taken for each sensor, one, by varying the resonance frequency values and the other by varying only the resonance frequency and the coupling coefficient values. As the resonance frequencies are taken from the experimental responses of all sensor systems, the above mentioned parameters are taken considering changing resonance frequency values. The other changing parameter is coupling coefficient. The first parameter named as (MSE (with changing coupling coefficient) = Mean area under the experimental curve X 100%) has been defined considering changing coupling coefficient values and the second parameter named as (MSE of individual set(w/o changing coupling coefficient) = MSE of nominal set(w/o changing coupling coefficient) X100%) has been defined considering no change in coupling coefficient values. This has been done considering the fact that, in the sensor systems, the aluminium substrates are glued with the piezo elements manually. Though similar metal substrates are attached with similar piezo elements with same amount of adhesive, there may be small differences in the amount of adhesive, the spread of adhesive over the piezo element surface, the placement of metal substrate over the adhesive. As a result, the coupling coefficient values differ from sensor to sensor, indicating different energy coefficient efficiency. This fact has been taken into consideration while choosing appropriate mode of vibration for the sensor systems.

MSE evaluates the difference between the estimated value and the true value of the quantity being measured. The MSE is used to determine to what extent the model fits the data. The MES provides the means of choosing the best estimator, a minimal MSE often indicates minimal variance and thus a good estimator. Here, the MSE of the nominal set has been taken as the minimal MSE. The first parameter measures how close the model is with respect to the experimental curve and the second parameter indicates how much the simulated curves for other sensor systems are close to the minimal MSE. As a whole these two parameters indicates the goodness of the model in thickness as well as the radial mode of vibration.

The values of the above mentioned parameters for the sensors in both of the modes are given in the Table 5 and Table 6. According to the table, the spread of $\pm\sigma$, i.e. 68% of total no of data (8 no of data) of "[MSE(with changing coupling coefficient) / Mean area under the experimental curve] X100%" on either side of nominal set value ranges between 6:1428 to 10:5710 in thickness mode and 7:5112 to 9:4224 in radial mode. Similarly, the spread of $\pm\sigma$, i.e. 68% of total no of data (8 no of data) of "[MSE of individual set(w/o changing coupling coefficient) / Mean Square Error of nominal set(w/o changing coupling coefficient)] X100%" on either side of nominal set value ranges between 0:0126 to 272:0946 in thickness mode and 78:2835 to 154:0305 in radial mode.

From the discussion, it can be said that

1. The spread of the two above mentioned parameters are much smaller in case of radial mode of vibration than that of the thickness mode. It signifies the fact that for radial mode the data are more concentrated at the nominal set value and that is why the radial mode of vibration is more appropriate for this frequency range.

2. From the Table 2and 4 the range of real component of coupling coefficient in thickness mode is higher than that of the radial mode, which signifies that the energy conversion is also more efficient in radial mode for this frequency range. The imaginary component value of coupling coefficient is also small in radial mode, indicating less amount of loss in energy conversion in the specified frequency range.

3. The imaginary component value of resonance frequency is also very very high for thickness mode of vibration.

From this, it can be said that the radial mode of vibration is suitable for our application and for this frequency range.

Modelling of the Sensor System attached with dental implant and prediction of nominal resonance frequency:

The sensor systems discussed here are to be used to measure stability of the dental implant placed inside the jaw. As shown in the Fig 1, there is a groove in the extended arm of the sensor to hold the implant. The implant has been placed inside the groove with the screw attached with the implant. The dental implants used in this purpose are made by "BIOHORIZONS". The implants are made by titanium alloy (Ti-6Al-4V). Four different types of dental implants are taken. They differ in their dimensions. The dimensions are given as (diameter X lengths). The mass of the implants (M) and their dimensions are given below:

1. 3:5mm X 9mm, named as DI1, M = 0.32 gm
2. 3:5mm X 12mm, named as DI2, M = 0.394 gm
3. 4mm X 9mm, named as DI3, M = 0.394 gm
4. 4mm X 12mm, named as DI4, M = 0.515 gm

The dental implant image has been given in Fig. 4 below:

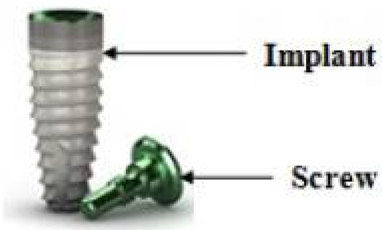

Fig. 4 Dental Implant

Experimental Procedure:
Among the twelve sensor systems mentioned earlier, nine sensor systems are taken and each of them are attached with all four different implants. They are excited with a sinusoidal voltage of 1 volt p-p and 1 to 20 kHz variable frequency, hence the same excitation used for the sensor systems and their responses are taken using the same LCR meter. As a whole there are four sets of responses corresponding to four types of implants and each set is having nine responses.
Modelling and Validation:
The sensors with dental implants are modelled based on the shift in resonance frequencies. The resonance frequency of the sensor system with dental implant has been shifted to a certain amount from the resonance frequency of only the corresponding sensor system. The dental implants while adding with the sensors are increasing the mass of the systems and also affecting the spring constants of the systems. This is the reason that why the resonance frequencies are shifting. The shift in resonance frequencies with the dental implants are given in the Table 7.
The resonance frequency of any object can be written as:

$$Resonance\ Frequency = \frac{1}{2\pi}\left(\frac{Spring\ Constant}{Mass}\right)^{1/2} \quad \text{.......................................(15)}$$

here, the mass includes the mass of the sensor and the mass of the implant. The mass of the implant is written in terms of its diameter and length as:

$$M = c * \varphi^2 * l_{(DI)} \quad \text{.......................................(16)}$$

where c is a constant includes π/4, density and volume-constant φ and l(DI) are given in the list of symbols.
Using this formula, c value has been calculated for all the four dental implants and is given in the Table 8. According to resonance frequency formula, the mass and the spring constant of an object are to be known to estimate the resonance frequency of that object. Here the resonance frequencies of the sensors and the sensors attached with implants can be found out from the experimental responses. The mass of the implants and the mass of the sensors are also known. So, the spring constant of the sensor systems (k_s) and the sensor systems with the dental implants (k_i) can be calculated. Now k_i differs from k_s due to the addition of the implant with the sensor system. The spring constant k_i is related not only with the diameter and length of the implant, but also on the type of joint between the sensor and the implant. As the implant is screwed into the sensor groove, the no of turns made to place the implant to the groove, the position of the implant inside the groove, the length of the screw inside the implant, all theses parameters affect the spring constant of the system. The implant has been connected with the sensor systems manually. Though enough precautions are taken to screw the implant inside the sensor groove, differences are there in the above mentioned points while placing the implants. That is why, the same implants, while attached with different sensors are showing different resonance frequencies, hence different spring constants. This has been incorporated into the modelling in terms of a constant, named as α which is different for different sensors even for a particular implant. In other words, α value indicates mainly the goodness of the attachment of the implant with the sensor system, hence high value of α should provide small shift in resonance frequency and vice versa.
The relation between k_i and k_s are expressed in terms of α, φ and $l_{(DI)}$ as follows:

$$k_i = k_s * \alpha * \varphi^{(0.03)} * \left(\frac{1}{l_{(DI)}}\right)^{\frac{1}{80}} \quad \text{.......................................(17)}$$

Initially the expression $\alpha * \varphi^{(0.03)} * \left(\frac{1}{l_{(DI)}}\right)^{\frac{1}{80}}$ has been estimated as a constant and the relation between k_i and k_s was expressed as k_i = Constant * k_s.

Then the constant term has been divided among the three parameters α, φ and $l_{(DI)}$ to indicate the contribution of the implant characteristics for deciding the resonance frequency of the total system. The contribution of implant characteristics have been decided on the basis of best fitting principle. α values calculated for different sensors and different implants are given in the Table 9.
From the table 7 and table 9 it can be seen that for every dental implant, minimum shift in resonance frequency provides maximum value of α and maximum shift in resonance frequency provides maximum value of α. As it is mentioned earlier that the α should have high value for small shift in resonance frequency low value for large shift in resonance frequency. This fact is also supported by the Table 9.
The total shift in resonance frequency has been divided into nine groups. Depending upon the group, the sensor systems with dental implants are taken together and their α values are averaged. This means

every group of "shift in resonance frequency" is having an average α value. Group wise average alpha values are given below:

1. Group1: ≤ 0:2 KHz, average α = 1.3199
2. Group2: > 0:2 kHz but ≤ 0:4 kHz, average α = 1.1989
3. Group3: > 0:4 kHz but ≤ 0:6 kHz, average α = 1.1510
4. Group4: > 0:6 kHz but ≤ 0:8 kHz, average α = 1.0729
5. Group5: > 0:8 kHz but ≤ 1:0 kHz, average α = 0.9951
6. Group6: > 1:0 kHz but ≤1:2 kHz, average α = 0.9235
7. Group7: > 1:2 kHz but ≤ 1:4 kHz, average α = 0.8554
8. Group8: > 1:4 kHz but ≤1:6 kHz, average α = 0.8629
9. Group9: > 1:6 kHz but ≤1:8 kHz, average α = 0.7944

Using the c values of each implant, average α value of each group, mass of the implants as well as the sensors and the relation between k_i and k_s, the resonance frequencies of the "Sensors with dental implants" are formulated as follows:

$$RF_i = \frac{1}{2\pi}\left(\frac{k_s * \alpha * \varphi^{(0.03)} * \frac{1}{l_{(DI)}}^{\left(\frac{1}{50}\right)}}{Mass\ of\ sensor + \left(c * \varphi^2 * l_{(DI)}\right)}\right)^{\frac{1}{2}} \quad \text{......(18)}$$

Using the above formula resonance frequencies are calculated and percentage error with the experimental values have been calculated which are given in the Table 10, Table 11, Table 12 and Table 13.

From the above tables, it can be said that the calculated resonance frequencies are very much closer with the experimental resonance frequency and the percentage error for all the cases lie within 4.2%, which is quite acceptable. As the error is much smaller in all the cases, so it can be said that α values estimated are quite satisfactory and it ranges within 1:0572±0:2628. On the other side, if the nominal resonance frequency is known, using the resonance frequency formula the dental implant characteristics can be predicted.

Table 1: Parameter values same for all cross sensor responses in thickness mode

Parameter names	Parameter values
$D_3\,(m)$	1
$C_{33}^{D}(N/m^2)$	$2\times 10^{10} + 3\times 10^{12} i$
$C_{s}^{D}(N/m^2)$	$5\times 10^{11} - 10^{14} i$
$\beta_{33}^{S}(F/m)$	$205\times 10^{12} + 10^{8} i$
$v_p(m/s)$	$16 - 16i$
$v_s(m/s)$	$14 - 14i$

Table 2: Parameter values different for different cross sensor responses in thickness mode

Piezo Sets	$k_t^{'}$	$f_p = f_s\ (Hz)$
set1, set2, set3	0.01778, 0.01781, 0.01777	6757- 6757i
set4, set5, set6	0.01089, 0.01089, 0.01088	6181- 6181i
set7, set8, set9	0.01442, 0.01437, 0.01437	7141- 7141i
set10, set11, set12	0.0195, 0.0195, 0.0194	6225- 6225i

$$k_t = k_t^{real} + k_t^{imag}, f_p = f_S = f^{real} + f^{imag}$$

$$k_t^{imag} = 0.115i, f^{real} = f^{experimental}, f^{real} = -f^{experimental}\ i$$

Table 3: Parameter values same for all cross sensor responses in radial mode

Parameter names	Parameter values
$C_{11}^{p}(N/m^2)$	$57\times 10^{6} + 10^{7} i$
$C_{11}^{s}(N/m^2)$	$2\times 10^{11} + 10^{8} i$
$\varepsilon_{33}^{p}(F/m)$	$5.56\times 10^{-4} + 10^{-10} i$
$v_p(m/s)$	$12000 + 10i$
$v_s(m/s)$	$12000 + 10i$

Table 4: Parameter values different for different cross sensor responses in radial mode

$$k_p = k_p^{real} + k_p^{imag}, f_p = f_s = f^{real} + f^{imag}$$

$$k_p^{imag} = 0.115i, f^{real} = f^{experimental}, f^{imag} = 100\,i$$

Piezo sets	k_p'	$f^{real}(Hz)$
set1, set2, set3	0.218, 0.219, 0.218	6757
set4, set5, set6	0.159	6181
set7, set8, set9	0.175, 0.174, 0.174	7141
set10, set11, set12	0.202	6225

Table 5: Statistical analysis for cross type sensors in thickness mode:

Sensor Sets	[MSE(with changing k_t) / Mean area under the experimental curve]x100%	[MSE of individual set(w/o changing k_t) / MSE of nominal set(w/o changing k_t)] x 100%
Nominal Set	6.7368	100
set1	10.5448	0.0247
Set2	10.5711	0.02457
Set3	10.5711	0.02456
Set4	6.7407	3.5183E-05
Set5	6.7345	3.5182E-05
Set7	6.1428	0.01260
Set8	6.1756	0.01242
Set9	6.1740	0.01242
set10	13.3936	271.9939
set11	13.3754	271.5422
set12	13.3990	272.0946

Table 6: Statistical analysis for cross type sensors in radial mode:

Sensor Sets	[MSE(with changing k_p) / Mean area under the experimental curve] x100%	[MSE of individual set(w/o changing k_p) / MSE of nominal set(w/o changing K_p)] x 100%
Nominal Set	9.3730	100
set1	9.4009	154.5099
Set2	9.4224	154.0305
Set3	9.4224	154.0305
Set4	9.3878	100.2142
Set5	9.3799	100.1059
Set7	7.5112	78.4187
Set8	7.5523	78.3626
Set9	7.5458	78.2835
set10	14.3445	249.4372
set11	14.3797	249.5809
set12	14.4094	249.9524

Table 7: Shift in RF (resonance frequencies) while adding dental implants with cross type sensors systems:

Sensor names	shift in RF with DI_1 (kHz)	shift in RF with DI_2 (kHz)	shift in RF with DI_3 (kHz)	shift in RF with DI_4 (kHz)
Sensor1	1.53	1.72	0.96	0.96
Sensor2	0.58	0.58	0.77	0.58
Sensor3	0.96	0.96	0.77	0.77
Sensor4	0.77	0.57	0.77	0.77
Sensor5	0.96	0.96	0.57	1.15
Sensor6	1.16	1.35	1.35	1.54
Sensor7	1.54	1.54	1.34	1.54
Sensor8	0	0.39	0.39	0.2
Sensor9	1.15	0.77	0.96	0.77

Table 8: c value of the implants:

Dental implant names	*c(kg=m³)*
DI_1	0.0029×10^6
DI_2	0.0027×10^6
DI_3	0.0027×10^6
DI_4	0.0027×10^6
DI_5	0.0027×10^6

Table 9: α values for different sensors and for different dental implants:

Sensor names	α for DI_1	α for DI_2	α for DI_3	α for DI_4
Sensor1	0.8055	0.7944	0.9883	1.0572
Sensor2	1.1088	1.1691	1.0972	1.2452
Sensor3	0.96689	1.0207	1.0698	1.1570
Sensor4	0.9873	1.1080	1.0235	1.0995
Sensor5	0.9524	1.0042	1.1241	1.0029
Sensor6	0.8748	0.8604	0.8488	0.8509
Sensor7	0.8425	0.8852	0.9243	0.9381
Sensor8	1.2811	1.2070	1.1907	1.3587
Sensor9	0.8929	1.0462	0.9763	1.1027

Table 10: Calculated resonance frequencies for different sensors with DI1:

Sensor names	Experimental resonance freq(kHz)	Calculated resonance freq(kHz)	% Error
Sensor1	6.37	6.5936	3.5105
Sensor2	7.71	7.8559	1.8918
Sensor3	6.18	6.2701	1.4571
Sensor4	5.98	6.2342	4.2509
Sensor5	5.98	6.1132	2.2279
Sensor6	5.98	6.1446	2.7527
Sensor7	6.94	7.0242	1.2114
Sensor8	7.14	7.2481	1.5139
Sensor9	6.56	6.6721	1.7085

Table 11: Calculated resonance frequencies for different sensors with DI2

Sensor names	Experimental resonance freq(kHz)	Calculated resonance freq(kHz)	% Error
Sensor1	6.18	6.1756	0.0708
Sensor2	7.71	7.6436	0.8608
Sensor3	6.18	6.0969	1.3454
Sensor4	6.18	6.1058	1.2007
Sensor5	5.98	5.9478	0.5390
Sensor6	5.79	5.7690	0.3629
Sensor7	6.94	6.8467	1.3440
Sensor8	6.75	6.7195	0.4524
Sensor9	6.94	7.0231	1.1976

Table 12: Calculated resonance frequencies for different sensors with DI3

Sensor names	Experimental resonance freq(kHz)	Calculated resonance freq(kHz)	% Error
Sensor1	6.94	6.9729	0.4740
Sensor2	7.52	7.4474	0.9658
Sensor3	6.37	6.3891	0.3000
Sensor4	5.98	6.1312	2.5279
Sensor5	6.37	6.4554	1.3403
Sensor6	5.79	5.8203	0.5236
Sensor7	7.14	6.8781	3.6676
Sensor8	6.75	6.7810	0.4591
Sensor9	6.75	6.8231	1.0832

Table 13: Calculated resonance frequencies for different sensors with DI4

Sensor names	Experimental resonance freq(kHz)	Calculated resonance freq(kHz)	% Error
Sensor1	6.94	6.7277	3.0593
Sensor2	7.71	7.4057	3.9463
Sensor3	6.37	6.1283	3.7945
Sensor4	5.98	5.9023	1.2994
Sensor5	5.79	5.5511	4.1269
Sensor6	5.6	5.6347	0.6192
Sensor7	6.94	6.6504	4.1722
Sensor8	6.94	6.8339	1.5290
Sensor9	6.94	6.8402	1.4375

CONCLUSION

In this study, a cross type sensor system attached with dental implants has been modelled to predict the nominal resonance frequency of the implant and the total system. The modelling of the sensor system has been done in two different modes of vibration, thickness and radial mode of vibration. As it is already mentioned earlier that the mode of vibration of the piezo with which the cross shaped metal substrate is attached, depends on the frequency range. Thickness mode is for high frequency range whereas the radial mode is for low frequency range. But this range of frequency, i.e. high and low cannot be exactly defined. It varies from piezo to piezo. From the modelling the appropriate mode of vibration for our purpose has also been decided. It has been mentioned that the radial mode of vibration is suitable for our purpose in the
mentioned frequency range i.e. 1 to 20 KHz.

When the cross type sensors are attached with four different types of dental implants, there is a shift in resonance frequency. The shift in resonance frequency denotes the addition of mass and the goodness of the attachment between the sensor and the dental implant. The factor reflecting the goodness of the attachment is noted as α and are approximated for different shift of resonance frequencies. It is already mentioned that α value ranges within 1:0572±0:2628. Taking these α values the resonance frequencies are calculated which are very close to the actual resonance frequencies and the error is within 4.2%. These simulated nominal resonance frequencies of the dental implants will help to predict the behaviour of the total system when placed inside the jaw to measure the actual in vivo dental implant stability. The nature of the vibration as well as the nominal resonance frequency of the system are very important parameters for measuring the stability of the dental implant as they provide guideline towards choice of frequency and amplitude of excitation voltage. As the excitation voltage given to the dental implant, placed inside the jaw of a human being, is actually going to be directly applied to the jaw and if it is above the safety limit of particular case, it may cause severe damage to human being. That is why this present study will provide a guideline not only towards the choice of proper dental implant and proper mode of vibration but also towards the choice of proper excitation voltage while measuring the stability of the dental implant using RFA technique.

LIST OF SYMBOLS USED:

1. d = Thickness of the piezo element i.e. the distance between the two electrodes of the piezo
2. l = Effective thickness of the metal strip
3. a_P = Area of the piezo element
4. ε^S_{33} = Clamped permittivity of the piezo element with constant strain
5. ε^P_{33} = Clamped permittivity of the piezo element in radial mode
6. β^S_{33} = Inverse clamped permittivity of the piezo element with constant strain
7. ω = Range of values of input frequency
8. f_P = Resonance frequency of the piezo element
9. f_S = Resonance frequency of the metal strip
10. k_P = Electromechanical coupling coefficient of piezo element in radial mode
11. k_t = Electromechanical coupling coefficient of piezo element in thickness mode
12. $r_P = r_S$ = Radius of the piezo element = Radius of the metal strip
13. c_P = Radially clamped capacitance of the piezo element
14. v_P = Velocity of sound through the piezo element
15. v_S = Velocity of sound through thee metal strip

16. h_{33} = Electric field constant i.e. electric field in the direction 3 (z direction) per unit strain in the same direction.
17. C_{11}^P = Complex stiffness of the piezo element in radial mode
18. C_{11}^S = Complex stiffness of the metal strip with constant strain
19. C_{33}^D = Complex stiffness of the piezo element at constant D
20. C_S^D = Complex stiffness of the metal strip at constant D
21. RF_i = Resonance Frequency of sensor with Dental Implant
22. Φ= Diameter of the implant
23. $l_{(DI)}$ = Length of the implant
24. k_i = Spring constant of sensor with Dental Implant
25. k_s = Spring constant of the sensor
26. M = Mass of dental implant

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